Renewable and Sustainable Energy Reviews 31 (2014) 439–445

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of vacuum tube based solar cookers with the experimental determination of energy and exergy efficiencies of a single vacuum tube based prototype

Suhail Zaki Farooqui *

Faculty of Engineering Sciences, National University of Sciences & Technology, Islamabad, PNS—JAUHAR, H.I. Rahamatullah Road, Karachi 75350, Pakistan

ARTICLE INFO

Article history:
Received 13 August 2013
Received in revised form
29 October 2013
Accepted 16 December 2013
Available online 15 January 2014

Keywords:
Solar cooker
Solar energy
Vacuum tube based solar cookers
Energy and exergy

ABSTRACT

Solar cookers may be generally classified into direct and indirect types. The direct types include the box type and parabolic type, while the indirect types include the vacuum tube based cookers. This paper reviews the gradual progress made in the second type. The energy and exergy analysis of a single vacuum tube based prototype has been carried out experimentally. Performance parameters indicate a high peak exergy power of 55.6 W, while the temperature difference gap at half power is 38.75 K and the quality factor is 0.042. The energy efficiency of the cooker is 20–30%, while the exergy efficiency is 4–6%. These results make this compact single family solar cooker comparable in performance to large community based Scheffer type solar cookers. Results have been compared to a number of other solar cooker types.

Contents

1. Introduction

Though there is a history for solar cooking since 1650, the first patent of a solar cooker was acquired by W. Adams in 1876 in India, who developed an octagonal oven with eight mirrors which cooked rations for seven soldiers in 2 h [1]. Cooking is one of the primary energy applications for people all over the world. For the strained economies of the developing countries, its share of energy consumption is even more [2]. Further, due to the growing realization of the environmental hazards of the use of fossil fuels and the impact of forest cutting on the ecological balance of the Earth, there is an ever greater necessity to develop more user and environment friendly cooking technologies [3]. The modern solar cookers were mainly developed after 1950s [4].

A vast majority of the world population lives in regions with abundant solar resource. It is well known that the total global energy demand is less than 0.01% of the solar radiation energy intercepted by Earth. It is therefore quite natural to develop feasible technologies for the harnessing of solar energy to its fullest extent. In addition to the addressing of the above mentioned issues, solar cooking offers other advantages like no recurring costs, energy independence and high nutritional value

* Tel.: +92 21 37681668; fax: +92 21 9040112.
E-mail address: drsuzaki@hotmail.com (S. Z. Farooqui).

1364-0321/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.12.010

of food. Still, the public adaptation of solar cookers is substantially lower than their potential. The main reasons are lack of trust by the public, intermittent nature of sunshine and inconvenience in the usage of many types of solar cookers. The solar cooking technology is yet not fully mature as far as the user convenience is concerned, and requires modifications in their life styles and energy usage habits. For this reason, not only a lot of further work is required to make these technologies more user friendly, but also promotional schemes and public demonstrations are required for the successful commercialization of solar cookers as a substitute for conventional cooking devices [3].

Fundamentally, there are three broad classes of solar cookers—the box type, parabolic type and the vacuum tube based type. The box type is the simplest, cheapest and slowest type as it utilizes the green house effect to trap the solar radiation energy inside an airtight box. They typically require two dimensional solar tracking every 20–30 min. The maximum achievable temperatures fluctuate around 120–130 °C, and therefore they are suitable only for water based cooking [5,6]. The parabolic types acquire the highest operating temperatures and are fastest in cooking, but require two dimensional solar tracking every 4–5 min. Reflection of high intensity solar radiation from the parabola may cause discomfort to the users. Their larger sizes are prone to wind caused damages. The vacuum tube based solar cookers either require one dimensional solar tracking or no tracking at all. Their operating temperatures and efficiencies are high, and they are relatively more user friendly. In this paper, a review has been carried out on the development of these types of solar cookers. Further, experimental determination of the energy and exergy efficiency of a recently proposed single vacuum tube based prototype has been carried out, and results are compared with the other major types.

2. Vacuum tube based solar cookers—An overview

While all the above mentioned types of solar cookers may be effectively used for the cooking of food when there is ample sun, vacuum tube based cookers have the special advantage that either they do not require solar tracking or they require only one-dimensional tracking and they attain higher cooking temperatures more quickly.

The first vacuum tube based solar cooker was reported by Balzar et al. [7] in 1996. Their system consisted of six double walled evacuated tubes mounted in parallel over successively curved aluminum reflectors. A long integrated copper heat pipe was inserted inside each vacuum tube. All the heat pipes were eventually connected to an aluminum plate. The plate that acted as heat sink in this case, was inserted inside a well insulated box that acted as the cooking chamber. A lid was provided at the top of this chamber to place any cooking pan directly over the oven plate. This cooker attained a maximum cooking temperature of 203 °C in about 3.5 h, while the maximum temperature attained with solar tracking and addition of booster mirrors was 252 °C in slightly less than 3 h. The effects of the reflector designs and material properties on the efficiency of this cooker were investigated in 1997 [8].

Stumpf, Balzar and others performed further experiments with the above vacuum tube based solar cooker in 2001 [9]. In one experiment, a flat plate collector with double glazed glass sheet (2.18 m^2 absorber area) was used with ten heat pipes, instead of the six vacuum tube panel. In the other experiment, the size of the vacuum tube panel was doubled to house twelve vacuum tubes instead of six. A mathematical model was developed and a comparative study was carried out for all three systems, and it was concluded that the vacuum tube system was most suitable for cooking with 2–3 h of preheating before adding the food stuff to the cooker. The maximum oil temperature of 231 °C was reached with the double-stage and 207 °C with the single stage vacuum tube system. The flat plate system showed a very high thermal conductivity, but reached a maximum temperature of 164 °C in 5 h.

Another vacuum tube based community solar pressure cooker was experimented and performance evaluated by Kumar et al. in 2001 [10]. Their collector contained twelve vacuum tubes mounted over an aluminum cusp rippled reflector, and were directly connected to a heat exchanger. Water was circulated through a pipe connecting a pressure cooker to the heat exchanger. The vacuum tubes were filled with a high boiling point fluid, which got vaporized at high temperatures, rose to the heat exchanger, and transferred its heat to the circulating water. This arrangement was reported to boil 14 kg of water in 140 min, from an initial temperature of 32 °C. The optimum cooking temperature was established at 120 °C according to the pressure cooker specifications. Very good correlation was found between the theoretically predicted and experimentally measured temperatures.

Essen tested a solar cooker in 2004 with similar configurations as that of Balzar et al. but with three different refrigerants and water, filled inside the heat pipes [11]. The refrigerants they used were Freon 22, Freon 122a and Freon 407C. In order to increase the heat transfer area, the coiled heat pipes were embedded in Mobiltherm 605—a thermal fluid, in the condenser section. The thermal fluid also provided a means for heat storage to keeping the food warm in the evenings. The collector panel was covered with a glass sheet and was further evacuated. The maximum temperature achieved in the cooking chamber was 175 °C in 3.5 h with seven liters of edible oil. The performance of refrigerant Freon 407C was reported to be the best amongst the three, due to its lower boiling point of −43.56 °C and higher latent heat of vaporization of 243.8 kJ/kg.

Sharma et al. carried out experiments with the same type of evacuated tube solar collector as that of Balzar et al. [7], with a phase change material (PCM). They used commercial grade erythritol ($C_4H_{10}O_4$) as PCM, having a melting point of 118 °C and latent heat of fusion of 339 kJ/kg [12]. Their experiments showed the possibility of using PCM in conjunction with the evacuated tube solar collectors for late hour cooking after the sun set.

3. A vacuum tube based solar cooker using linear Freznel collector

Another single vacuum tube based solar cooker was recently reported [13]. It utilized a 122 cm × 183 cm linear Freznel collector bed with 17 plain mirror strips. The mirror strips were mounted on square steel pipes, which were fitted inside a wooden frame through bearings, and were rotatable on individual axes, as shown in Fig. 1. Circular Teflon discs were mounted on one end of each of

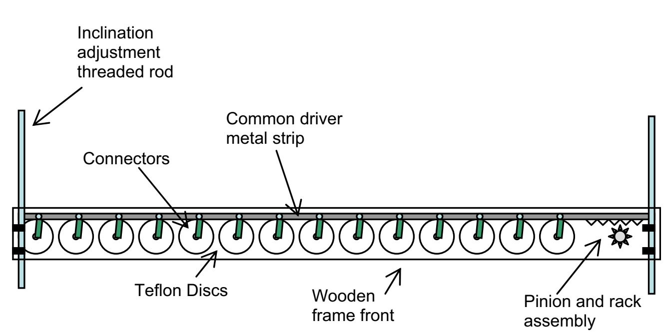

Fig. 1. Schematic cross sectional view of the synchronized tracking system for the primary reflector mirror strips. All the mirrors have to rotate by 0.5° as the sun moves by 1° through the sky. The tracking is performed by a motor connected to a tracking circuit.

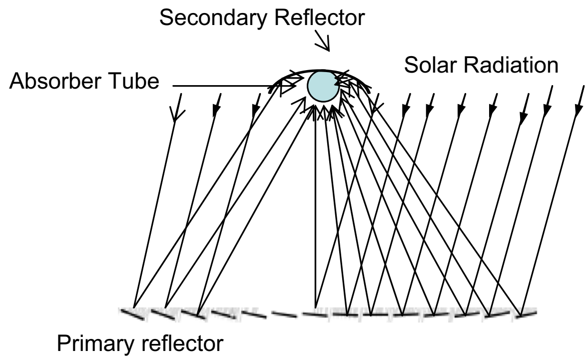

Fig. 2. Cross sectional view of the schematic diagram of a linear Fresnel collector. Laser aligned primary mirrors reflect the incoming light onto the absorber tube. Any leaked radiation strikes the secondary reflector and is reflected back to the tube.

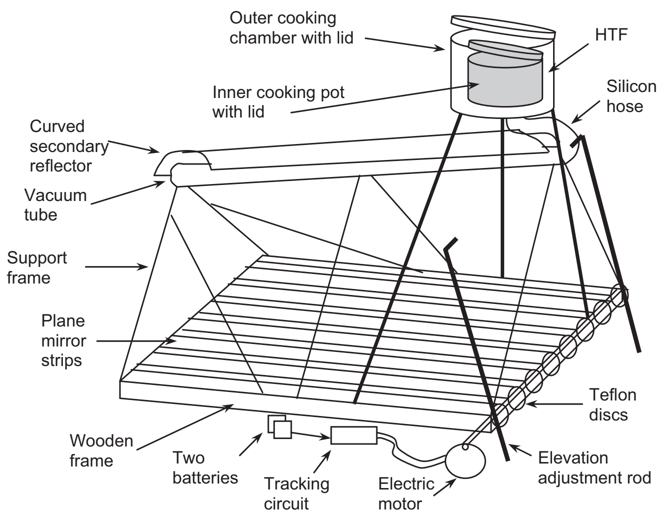

Fig. 3. Schematic diagram of the single vacuum tube based solar cooker using mini Freznel collector.

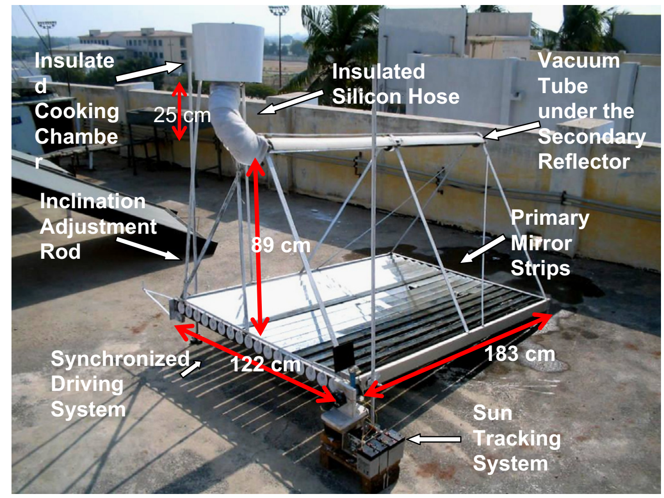

Fig. 4. The single vacuum tube based solar cooker using mini Freznel collector [13].

the steel pipes. All the discs were connected to a motion synchronizing aluminum strip. The aluminum strip was connected to a small low power and low speed DC motor through a pinion and rack assembly, to act as a common driver. The low speed motor was connected to a sun tracking circuit.

All the mirror strips were laser aligned at appropriate angles to reflect the incoming perpendicular parallel solar rays towards the fixed absorber vacuum tube mounted over the collector at a height. A secondary curved reflector mounted over the absorber tube reflected back any leaked radiation to it, as illustrated in Fig. 2. Provision was made through threaded end rods to allow the inclination adjustment of the entire collector assembly with respect to the horizon to maximize the efficiency.

The well insulated cooking chamber was connected to the top end of the vacuum tube through a high temperature tolerant silicon hose, and was well insulated from outside to minimize thermal losses, as shown in schematic Fig. 3. Along with the vacuum tube, the cooking chamber was half filled with a high boiling point thermal fluid, such as thermal or vegetable oil. The thermal fluid circulated between the vacuum tube and the cooking chamber through thermal siphoning. A frame supported the cooking chamber above the vacuum tube. A cooking pot containing the actual stuff to be cooked, was placed inside the cooking chamber. As per desire, this configuration permitted frequent interaction with the food, during the cooking process.

The tested prototype shown in Fig. 4, fed a nearly 250 W of average thermal power transfer capacity at 25° latitude location, and was built for nearly US$ 100. It offered fast cooking without frequent manual solar tracking. The overall thermal power transfer efficiency was measured to be nearly 30%. Temperatures of up to 250 °C were achieved. This cooker was therefore quite suitable for water based as well as oil based cooking and frying of food. Experimental results of this cooker indicated more than five times greater heat absorption capacity compared to a 60 cm × 60 cm conventional box type solar cooker. The average power consumption of the tracking circuit and motor was 4 W. It was operated for 10 s after 50 s intervals, through a timer.

4. Energy and exergy analysis

In order to assess the thermal performance of solar cookers of different geometries, an exergy based unified test protocol was proposed by Kumar et al. [14]. Exergy provides a measure of the potential of a given device to extract heat from its surroundings, as the device moves closer to the equilibrium with its surroundings. The exergy becomes zero as the system reaches an equilibrium state with its environment [15,16]. The exergy input to the solar cooker, same as the exergy of solar radiation, can be calculated using available solar radiation flux ($I^{\circ}A\Delta t$) as [14]:

$$E_{X_i} = I^{\circ} A\Delta t \times [1 + (T_a/T_s)^4 \times (1/3) - (4/3) \times (T_a/T_s)] \tag{1}$$

where T_a is the ambient temperature, T_s is the surface temperature of the sun, I° is the instantaneous solar radiation intensity perpendicular to the collector, A is the aperture area of the solar cooker/collector and Δt is the time interval, whereas the output energy of the system is equal to the energy gained by the material inside the solar cooker as:

$$E_{out} = m \times c \times \Delta T \tag{2}$$

where m is the mass of the material inside the solar cooker, c is the specific heat capacity and ΔT is the difference between the initial and final temperatures acquired during the time interval Δt.

For the exergy analysis however, the ambient temperature also plays a role in deciding the efficiency of a system. The exergy output of the system is expressible through [15]:

$$E_{xo} = E_{out} - mc \times T_a \times In \times (T_{wf}/T_{wi}) \tag{3}$$

where T_{wi} and T_{wf} are respectively the initial and the final temperatures of the material inside the solar cooker.

The exergy efficiency is thus given by:

$$\Psi = \frac{mc[(T_{wf}-T_{wi})-T_a ln(T_{wf}/T_{wi})]/\Delta t}{I^{\circ}[1+(1/3)(T_a/T_s)^4-(4/3)(T_a/T_s)]A} \tag{4}$$

while the exergy loss coefficient from the system is given by:

$$E_{Xloss} = (E_{Xi}-E_{Xo})/A\Delta t \times \delta T\ (W/km^2) \tag{5}$$

where δT is the difference between the water and the ambient temperature.

In order to carry out the energy analysis of the solar cooker, the instantaneous solar radiation intensity I over a horizontal surface is measured over a number of small time intervals, and converted to the intensity I° on the Freznel collector, as shown in Fig. 5, where the instantaneous solar altitude angle is α and the angle of inclination of the collector is β.

A graph plotted between output exergy power and the temperature difference between water and the ambient air, and fitting the data with a second order polynomial may be used to extract the peak value of exergy from the fitted curve [14]. The curve also provides the temperature difference gap, as the difference of temperature difference values corresponding to the half exergy power points. The exergy lost during the test may also be plotted against the temperature difference so as to estimate the overall heat loss coefficient of the cooker.

Therefore:

$$I^{\circ}(t) = I(t) \times sin \times (\alpha(t)+\beta)/sin(\alpha(t)) \times (W/m^2) \tag{6}$$

The solar altitude angle α is given by [17]:

$$\alpha = sin^{-1}[sin \times \delta \times sin \times \varphi + cos \times \delta \times cos \times \omega \times cos \times \varphi]\ (degrees) \tag{7}$$

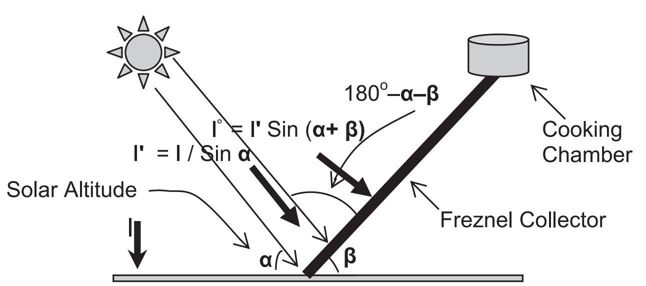

Fig. 5. Intensity of the incident solar radiation I° on the Freznel collector, where I is the intensity of radiation on the horizontal surface and I' is the intensity on a surface held perpendicular to the sun, when the solar altitude angle is α and the angle of inclination of the collector with respect to horizon is β.

where φ is the latitude of the location and ω is the hour angle, defined as:

$$\omega = 15 \times (t_s - 12)\ (degrees) \tag{8}$$

where t_s is the local solar time in hours, related to the longitude of the test location, and δ is the declination angle, given to one degree accuracy by:

$$\delta = sin^{-1}[0.39795 \times cos \times [0.98563 \times (N-173)]]\ (degrees) \tag{9}$$

N is the number of day of the year starting from January 1. All angles in Eqs. (6)–(9) are measured in degrees.

If Δt be the constant time interval between n observations, during which the temperature of the HTF changed by ΔT, then the total exergy input to the solar cooker will be:

$$E_{in} = \sum_{1=1}^{n} \times E_{Xi}(t_i) \tag{10}$$

Comparison between Eqs. (10) and (2) provides the energy efficiency € of the solar cooker by:

$$\in\ = E_{out}/E_{in} \tag{11}$$

5. Experimental results

In order to determine the exergy of the single vacuum tube based solar cooker, three experiments were conducted on March 25, March 28 and April 3, 2013 at Karachi (25° latitude and 67° longitude). The cooking chamber and the vacuum tube were filled with 5 l of water. The Freznel collector, as described in Section 3, having an effective primary reflector area of 1.52 m^2 was inclined at an angle of 26° with respect to the horizon, facing south. Readings of water temperature in the cooking chamber and ambient temperature (Figs. 6 and 7) and solar radiation intensity on a horizontal plane (using Apogee SP110 Pyranometer) were

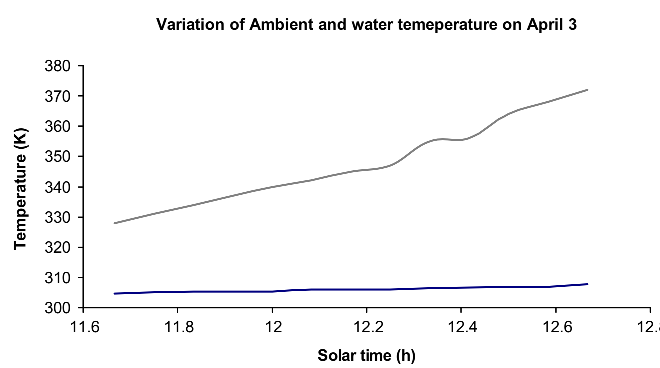

Fig. 7. Plot similar to Fig. 4 for April 3, 2013, during 11:35 to 12:40 h (solar time).

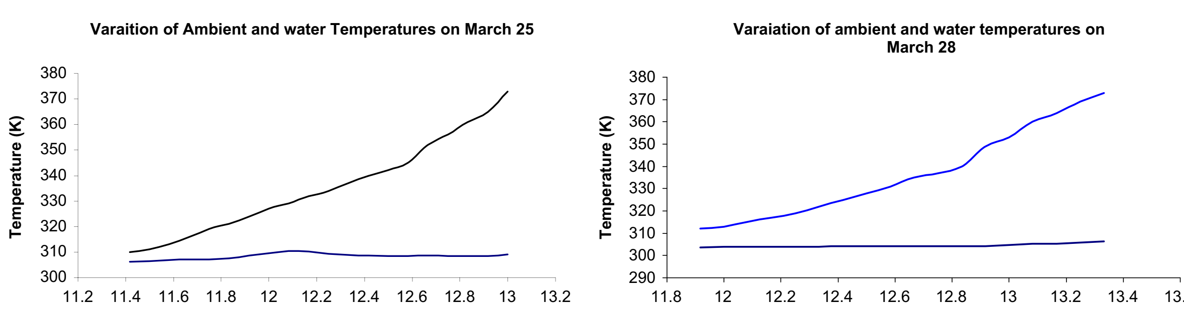

Fig. 6. Plots of 5 kg of water temperature (top curve) in the single vacuum tube based solar cooker, and the ambient temperature (bottom curve) on March 25 and March 28, 2013, at test location, during 11:20 to 13:00 h and 11:50 to 13:20 h, respectively (solar time).

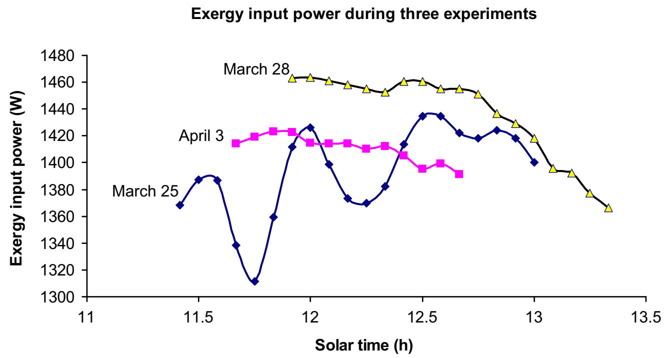

Fig. 8. Exergy power input (W) to the solar cooker on March 25, March 28 and April 3, 2013, at the test location. Surface temperature of the Sun is taken at 5860 K.

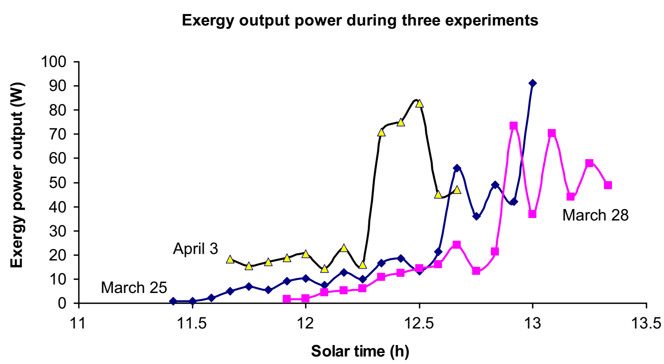

Fig. 9. Exergy output power of the solar cooker on March 25, March 28 and April 3, 2013, at the test location.

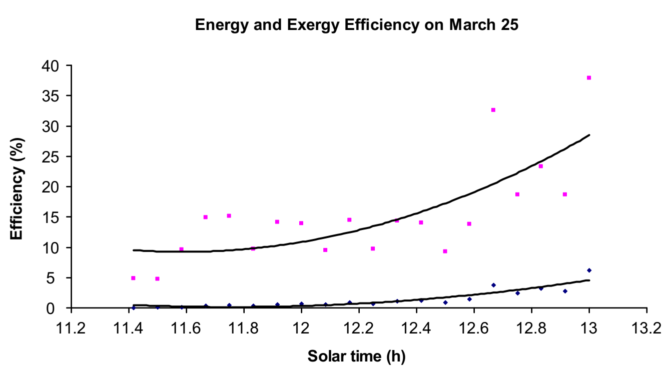

Fig. 10. Energy and exergy efficiencies of the solar cooker as measured on March 25, 2013.

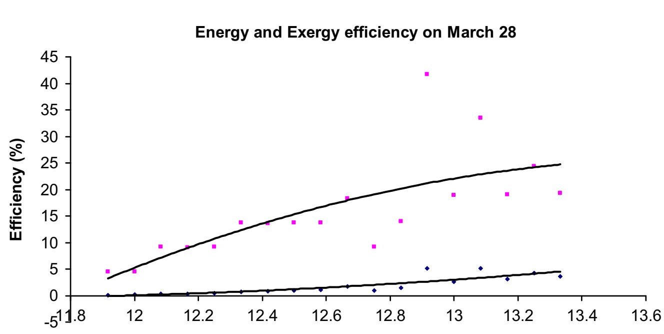

Fig. 11. Energy and exergy efficiencies of the solar cooker as measured on March 28, 2013.

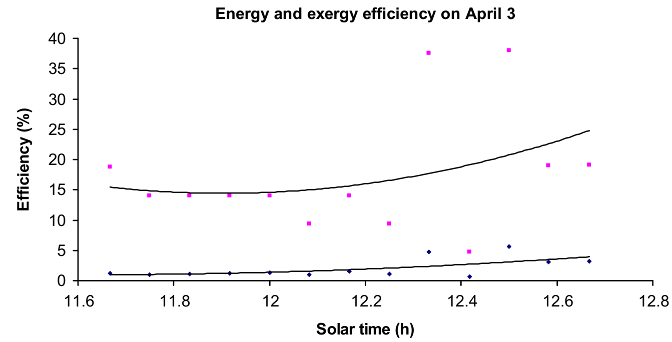

Fig. 12. Energy and exergy efficiencies of the solar cooker as measured on April 3, 2013.

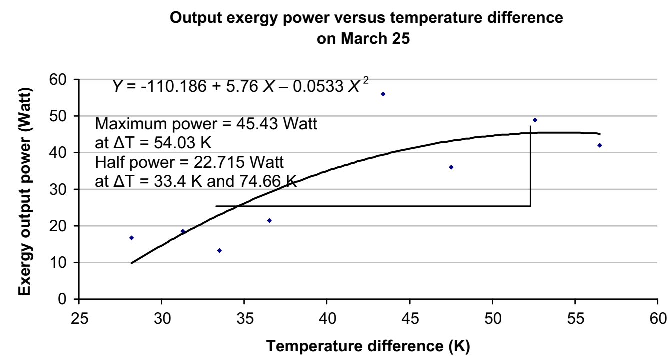

Fig. 13. Second order polynomial fit to the exergy output power plotted versus the temperatures difference on March 25, 2013.

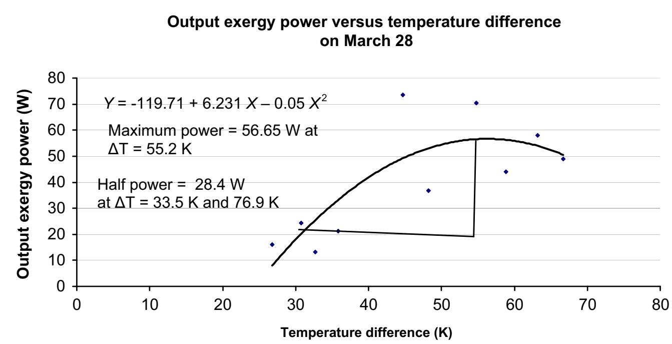

Fig. 14. Second order polynomial fit to the exergy output power plotted versus the temperatures difference on March 28, 2013.

measured at 1 min intervals, and 5 min averages were recorded. The instantaneous solar radiation intensity over a horizontal surface $I(t)$ was converted to the intensity $I^{\circ}(t)$ perpendicular to the Freznel collector using Eq. (6).

The exergy power input to the solar cooker is calculated using Eq. (1) and results are plotted in Fig. 8 for the three experiments.

The exergy output power of the solar cooker is determined using Eq. (3) and results are plotted in Fig. 9 for the three experiments.

The energy efficiency as determined using Eq. (11) and the exergy efficiency as calculated using Eq. (4), are plotted in Figs. 10-12. The top curves in each figure show the energy efficiency.

The plots of output exergy power E_{xo} [Eq. (3)] versus the temperature difference [$\delta T = (T_{wf} + T_{wi})/2 - T_a$] are shown in Figs. 13-15, for March 25, March 28 and April 3, 2013, respectively. The results are fitted to second order polynomials.

The plot of the exergy loss ($E_{Xloss} = E_{Xi} - E_{xo}$) versus the temperature difference between water and the ambient air [$\delta T = (T_{wf} + T_{wi})/2 - T_a$], on March 28, 2013 is shown in Fig. 16.

6. Discussion

The results shown in Fig. 8 indicate that the exergy input power remained between 1300 W and 1470 W during the test periods on all three days of the experiments, while the exergy output power remained below 90 W, as seen in Fig. 9. The energy efficiencies as plotted in the top curves of Figs. 10–12 show peak values of 25–30%, while the exergy efficiencies in the bottom curves show a maximum average value of 4.7%. The exergy output power (E_{xo}) plotted versus the temperature difference (δT) in Figs. 13–15 are fitted with a second degree polynomial. The peak exergy power in each case is determined by equating the derivative of the polynomial to zero. This curve provides a means to compare the performance of various types of solar cookers. The temperature difference gap at half peak power provides the most desirable working range of the solar cooker. The larger the working range, the better the performance. The average peak exergy power in three experiments is 55.6 W, with a half power temperature difference gap of 38.75 K. The product of these two quantities provides an important judgment criteria for determining the merit of a solar cooker. The peak exergy power in the above experiments occurs at an average temperature difference of 54.41 K.

The exergy loss data plotted in Fig. 16 versus the temperature difference is fitted with a least squares linear curve. Slope of this curve (2.63) divided by the aperture area (0.107 m^2 of the vacuum tube) provides the heat loss coefficient (W/K m^2) of the cooker. Further division by the amount of water (5 kg) gives the specific heat loss coefficient (W/K kg m^2). The ratio of peak exergy gained to the exergy lost at that instant maybe considered as the quality factor of a solar cooker. This parameter comes out to be 0.042. Table 1 compares the published performances of the various types of solar cookers with that of the single vacuum tube based one [14]. It can be easily inferred that the single vacuum tube based cooker out performs all other types of solar cookers in terms of performance measuring parameters, except the Scheffer type community solar cooker, where its comparative performance is nearly equal. But then, the Scheffer type cooker is a large community cooker, while the vacuum tube type is a small compact single family cooker.

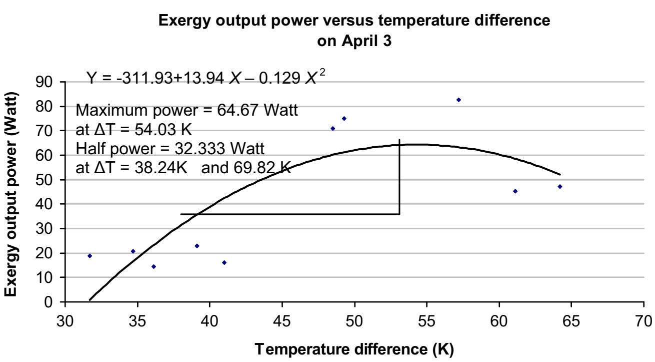

Fig. 15. Second order polynomial fit to the exergy output power plotted versus the temperatures difference on April 3, 2013.

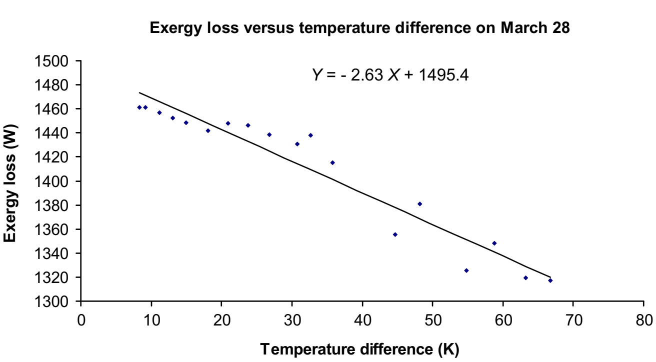

Fig. 16. Least squares fit to the exergy loss plotted versus the temperature difference for March 28, 2013.

7. Comparative performance with box type solar cooker

For the sake of further comparison with other conventional solar cooker designs, two box type solar cookers (60 cm × 60 cm and 46 cm × 61 cm) were simultaneously loaded with two kilograms of water each, along with the vacuum tube based solar cooker. Their two-dimensional manual tracking was carried out every 10 min. Results of the better box type performer (60 cm × 60 cm) and the vacuum tube type are plotted in Fig. 17. Comparison shows that the box type cooker took 174 min to raise the temperature of 2.0 kg of water from 43 °C to 100 °C, while the vacuum tube based cooker took 75 min to heat 4.5 kg of water for the same temperature range. The reason for loading the vacuum tube based

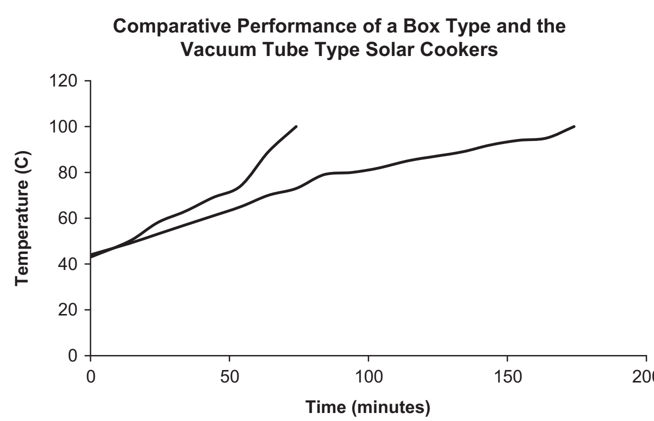

Fig. 17. Plot of comparative performance of a box type versus the vacuum tube based solar cooker. Experiment started at 11:40 a.m. The vacuum tube based cooker boiled 4.5 kg of water in 75 min (top curve), while the box type cooker took 174 min to boil 2 kg of water (bottom curve).

Table 1
Comparison of the performances of the various types of solar cookers.

Solar cooker type	Peak exergy power (W)	Temperature difference gap at half power (K)	Peak exergy power and temperature difference gap product (W-K)	Heat loss coefficient (W/m^2 K)	Specific heat loss coefficient (W/km^2 kg)	Quality factor
SBC (box)	6.46	46.2	298.5	5.24	2.096	0.123
SK-14 (domestic)	18.21	40.374	735.3	40.35	8.07	0.106
Parabolic trough	6.92	23.15	160.198	47.73	7.58	0.087
Scheffer (community)	55.75	39.62	2208.815	54.125	2.706	0.099
Single vacuum tube	55.6	38.75	2154.5	24.58	4.916	0.042

cooker with more water (4.5 kg) is to half fill its cooking chamber along with the vacuum tube and silicon hose, while the same amount of water will take much longer to boil in the box type cooker. The results indicate that the average heat absorption capacity of the vacuum tube based solar cooker is 5.2 times greater than that of the conventional cooker. It can therefore cook food substantially faster than the other solar cookers.

These results are supported by the data presented in Table 1, where comparison of data in the first three columns for the SBC (Box—first row) versus single vacuum tube (last row) shows that the peak exergy power for the box type is 6.46 W, while it is 55.6 W for the vacuum tube type—8.6 times higher. Similarly, the product of peak exergy power and temperature difference gap is 298.5 W-K for the box type, while it is 2154.5 W-K for the vacuum tube type—7.2 times higher. Even though the specific heat loss coefficient and quality factor for vacuum tube type cooker are lower than that of the box type, these parameters may be improved by improving the external insulation of the cooking chamber, and reducing the length of the silicon hose connecting the vacuum tube to the cooking chamber. The maximum attainable temperature in the box type solar cookers is around 120 °C, while in the vacuum tube type it is 250 °C, making it suitable for all types of cooking, including frying which requires temperatures of around 200 °C. The single vacuum tube type solar cooker therefore, clearly outperforms the conventional box type sole cooker. The above prototype was manufactured for a total cost of US$ 102 excluding labor, compared to the price of a box type cooker available in the local market at US$ 40. The added advantages largely offset the added costs and complexity of the new system.

8. Conclusions

An overview of the historical development of vacuum tube based solar cookers has been presented in this paper, in addition to the experimental determination of the energy and exergy efficiencies of a recently reported single vacuum tube based solar cooker. Three experiments were carried out within ten days during the months of March and April 2013. Experimental curves of the ambient and water temperatures, exergy input power, exergy output power and energy and exergy efficiencies have been plotted for all three experiments. The exergy output power and the exergy loss have also been plotted against the temperature difference between the ambient air and the water inside the cooker. The exergy output data has been fitted with a second degree polynomial, while the exergy loss data has been fitted to a first degree polynomial. The average peak exergy power of the solar cooker (55.6 W) drawn from the first curve yields a value almost equal to that of Scheffer type community solar cooker (55.75 W). The exergy loss coefficient (24.58 W/m^2 K) is substantially less that that of the Scheffer type cooker (54.125 W/m^2 K). However, specific exergy loss coefficient (4.916 W/m^2 kg K) is more than that of the Scheffer type (2.706 W/m^2 kg K). This shows that while the exergy gain of the two types of solar cookers is almost equal, the exergy loss per unit mass is more for the vacuum tube type. Further, the quality factor (0.042), which is a measure of the peak exergy gain per unit exergy loss at the instant is also less than half compared to that of the Scheffer type (0.099). This is because of a larger fractional area of the cooking chamber per unit mass of water exposed to the ambient in case of the vacuum tube type cooker. The energy efficiency of the cooker is between 25% and 30%, while the exergy efficiency is 4–6%. Keeping in view the small compact size of the vacuum tube type solar cooker, all performance measuring parameters indicate that it is a substantially better single family performer compared to all other types, and is suitable for faster cooking of almost all types of food.

Acknowledgment

This work is sponsored by the Higher Education Commission of Pakistan under grant No. 20-1568/R&D/09/2023.

References

[1] Narayanaswamy S. Making the most of sunshine—a handbook of solar energy for the common man. India: Vikas Publishing House PVT Ltd; 2001; 72.
[2] Pohekar SD, Kumar D, Ramachandran M. Dissemination of cooking energy alternatives in India—a review. Renewable Sustainable Energy Rev 2005;9:379–93.
[3] Farooqui SZ. Prospects of renewable's penetration in the energy mix of Pakistan. Renewable Sustainable Energy Rev 2014;29:693–700.
[4] Muthusivagami RM, RVelraj R, Sethumadhavan R. Solar cookers with and without thermal storage—a review. Renewable Sustainable Energy Rev 2010;14(2):691–701.
[5] Farooqui SZ. A gravity based tracking system for box type solar cookers. Sol Energy 2013;92:62–8.
[6] Panwar NL, Kaushik SC, Kothari S. State of art of solar cooking: an overview. Renewable Sustainable Energy Rev 2012;16:3776–85.
[7] Balzar A, Stumpf P, Eckhoff S, Ackermann H, Grupp M. A Solar cooker using vacuum-tube collectors with integrated heat pipes. Sol Energy 1996;58(1–3):63–8.
[8] Balzar A, Stumpf P, Vajen K, Ackermann H. Effects of reflector designs and material properties on the efficiency of solar vacuum tube collectors—a ray tracing study. Optic Int J Light Electron Opt Opt 1997;111(1):39–43.
[9] Stumpf P, Balzar A, Eisenmann W, Wendt S, Ackermann H, Vagen K. Comparative measurements and theoretical modeling of single- and double-stage heat pipe coupled solar cooking systems for high temperatures. Sol Energy 2001;71(1):1–10.
[10] Kumar R, Adhikari RS, Garg HP, Kumar A. Thermal performance of a pressure cooker based on evacuated tube solar collector. Appl Therm Eng 2001;21:1699–706.
[11] Essen M. Thermal performance of a solar cooker integrated vacuum-tube collector with heat pipes containing different refrigerants. Sol Energy 2004;76:751–7.
[12] Sharma SD, Iwata T, Kitano H, Sagara K. Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit. Sol Energy 2005;78:416–26.
[13] Farooqui SZ. A vacuum tube based improved solar cooker. Sustainable Energy Technol Assess 2013;3:33–9.
[14] Kumar N, Vishwanath G, Gupta A. An exergy based unified test protocol for solar cookers of different geometries. Renewable Energy 2012;44:457–62.
[15] Petela R. Exergy of undiluted thermal radiation. Sol Energy 2003;74:469–88.
[16] Petela R. Engineering thermodynamics of thermal radiation for solar power utilization. New York: McGraw-Hill; 2010.
[17] Stine WB, Geyer M. Power from the sun, J.T. Lyle Center for regenerative studies. John Wiley & Sons, Inc.; 2001.